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Assessing hydrological effects and performance of low impact development practices based on future scenarios modeling

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ABSTRACT

Future scenarios modeling has been conducted to investigate the effectiveness of urban stormwater infrastructure and to cater to potential future changes. The changes of quantity and quality of urban stormwater, and attributable to climate change and urbanization, were examined and tested in four urban catchments based on future scenarios modeling. Based on our findings, we observed that there were different degrees of performance corresponding to 2-, 10-, and 100-year design storms. However, the general patterns and insights deduced were similar: (1) the peak runoff and water quality appeared to be impacted more significantly by urbanization factors than that due to climate change; (2) the influence from urbanization (increase intensity of land use and population density) was found to be more significant than that from land-use changes alone; (3) catchments with relatively rapid developing rates appeared to produce more serious adverse influence on the stormwater quabntity and quality; and (4) low impact developments as key adaptation practices could be potentially effective in mitigating adverse impacts of future changes on urban stormwater system. The methodology developed in this study could be useful for urban stormwater planning and testing the plan against future change scenarios as a result of urbanization and climate change.

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1. Introduction

Several potential future scenarios, including change in rainfall patterns, rising sea level and higher temperatures, may be caused by climate change following increasing greenhouse-gas concentrations (IPCC, 2014). It is also a well-known fact that climate change may lead to serious urban stormwater issues due to increased rainfall intensity and frequency of storms (Berggren et al., 2011). To develop adaptation or mitigation strategies, predictions of future climate change play a fundamental role in characterizing storm risks and better understanding the options of response to climate change (Zahmatkesh et al., 2014). The Scenario Model Intercomparison Project, i.e., the latest and primary activity within the Coupled Model Intercomparison Project Phase 6 (CMIP6), has provided multi-model climate projections (i.e., General circulation models, GCMs) and integrated assessment models based on alternative scenarios of future emissions and land-use changes (e.g., representative concentration pathways, RCPs and shared socio-economic pathways, SSPs) (O'Neill et al., 2016). A number of studies that had adopted GCMs to develop climatic change scenarios and their impacts on rainfall and runoff (Reshmidevi et al., 2017; Mehrotra et al., 2013) have been published. Such changes in storm characteristics could provide valuable inputs to future development plans for stormwater management, as part of larger urban development plans (Simonovic et al., 2016).

In addition to climate change, urban development significantly alters the catchment-scale hydrologic cycle as “virgin” lands are transformed into urban spaces and infrastructure (e.g., buildings, parking lots and roads) (Miguez et al., 2014). The larger proportion of impervious area generally leads to reduction of infiltration capacity and groundwater recharge (Dietz, 2007), with the undesirable consequences for the urban hydrologic cycle, for example, increased risks of urban flooding (Mugume et al., 2015; Wang et al., 2016a), deterioration of water quality in recipient water bodies

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(Zgheib et al., 2012), and damage to urban ecological environment through bank/bed erosion (Roy et al., 2008). However, changes in urbanization are often not sufficiently incorporated in climate change impact assessment studies (Pyke et al., 2011). Most reported studies have focused on either climate change or urbanization impacts as the driver to simulate future scenarios of the quantity and/or quality of surface runoff (Willuweit and O'Sullivan, 2013), when ideally both should be included in the assessment (Wernstedt and Carlet, 2012). However, only a handful of studies on stormwater management were carried out in the latter manner. Abdul-Aziz and Al-Amin (2016) investigated the sensitivity of stormwater quantity and quality in a coastal urban catchment (Miami River Basin of Florida) based on certain climate change scenarios and changing land use. Borris et al. (2016) considered both climate change and socio-economic factors in their assessment of stormwater quality in urban and suburban catchments of Östersund, Sweden. Wang et al. (2016b) developed a RCP-SSP matrix architecture simulating the scenarios of climate change and urbanization to assess the cost-effectiveness of bio-retention for stormwater management in Singapore. There is consensus that more such studies are needed, especially in urban catchments with different developments and land uses.

Recently, low impact development (LID) based on decentralization and source control have emerged and have become increasingly attractive measures to adapt to or mitigate the adverse hydrological impacts of rapid urbanization and climate change (Miguez et al., 2014). LID offers an innovative approach to manage surface runoff – one that does not rely on the conventional end-of-pipe structural methods but instead uniformly or strategically integrates stormwater controls throughout the urban landscape (Martin-Mikle et al., 2015). Used in combination, LID practices, which may include constructed wetlands, bioretention, rain gardens, green roofs and bioswales, can more closely mimic natural ecological and hydrological functions in a watershed. The water balance between runoff, infiltration, storage, groundwater recharge, and evapotranspiration, as well as improvement of stormwater quality through physical, chemical and biological processes could be achieved readily (Liu et al., 2015). However, there have been scarce reported studies on LID practices in response to the combined impacts of climate change and urban development. In view of the above, this study is designed to achieve the following objectives: (1) to examine the potential impacts of future changes in climate change and urbanization on stormwater for different urban catchments; and (2) to assess the performance of LID practices incorporated in urban catchments based on pertinent future scenarios. The methodology developed in this study can be used to develop climate change adaptation strategies for urban stormwater management (USM) in the context of an urban catchment under the local conditions.

2. Methodology

Future scenarios combining climate change and urbanization were simulated to make projection of the effects of changes in precipitation and land uses in four urban catchments. Then, a hydrological model was used to determine peak runoff and water quality corresponding to various future scenarios, and to evaluate the sensitivity of various hydrological parameters. Finally, the performance of selected LID practices corresponding to various future scenarios was examined (Fig. 1). In these future scenarios, climate change generally leads to "modified" storm events in terms of storm frequency, duration and intensity, while changes in runoff are driven by the surface characteristics, including changes in land use and imperviousness of the urbanizing catchments.

2.1. Study sites

Four urban catchments including two catchments in Singapore, a tropical island with an average of 2400 mm of annual rainfall, and two catchments in Shenzhen, a fast-growing city with an average of 1950 mm of annual rainfall in China, were selected as test catchments (Fig. 2). The first catchment, in Outram Park of Singapore, is a mixed commercial and residential (C-R-Singapore) area. It occupies 71 ha and is characterized by large fraction of impervious surface, with mostly commercial and residential land use. Similarly, the second catchment, located at Sha Tau Kok West of Shenzhen, has an area of 228 ha and is characterized by mostly residential and commercial land use, and is designated as C-R-Shenzhen area. The third catchment, in Jurong West of Singapore, is a mixed industrial and residential area (I-R-Singapore). It has an area of 787 ha, with a large fraction of impervious area, and includes mixed residential and industrial land use in a more suburban area. The fourth catchment which is located in Sha Tau Kok East of Shenzhen, is characterized by mixed industrial and residential land use (I-R Shenzhen). Table 1 contains a summary of the characteristics of these four test catchments. The baseline scenario which represented the present climate condition and land-use patterns, was used to establish a benchmark upon which comparison with future scenarios were made. As for the design storms, rainfall events of 2-, 10-, and 100-year recurrence intervals, lasting 90 min each (corresponding to 75 mm, 110 mm and 150 mm of rainfall depth in Singapore, and 75 mm, 96 mm, and 125 mm rainfall depth in Shenzhen, respectively), were selected to assess the hydrology performance in the test catchments (Public Utilities Board, 2013).

2.2. Global climate modesl (GCMs) and Regional Climate Models (RCMs)

The ensembles of GCMs extracted for Singapore and Shenzhen were assessed for their climate change projections and to extract representative key aspects of climate such as regional rainfall patterns (Marzin et al., 2015). Then, nine high-resolution downscaled projections with a 12 km horizontal resolution grid centered on Singapore and Shenzhen using the Met Office Hadley Centre (MOHC) Regional Climate Model (RCM) HadGEM3-RA were established. The selected ensembles of the drivers for the GCMs is as shown in Table 2. This subset of the RCM data was bias-corrected by matching the historical simulations of daily distributions of temperature, precipitation and relative humidity to observations using a quantile-matching methodology (Kendon et al., 2012; Harris et al., 2014; Marzin et al., 2015). The projected RCM rainfall data had a range from about 4.23 mm/day to 7.97 mm/day, and 5 out of 9 RCMs showed values within ± 10% of the observed local average precipitation (Kerkhoff et al., 2014; Yatagai et al., 2009; Marzin et al., 2015).

2.3. Future scenarios

2.3.1. Climate change scenarios

Climate change scenarios, which describe possible future developments of anthropogenic drivers of climate change consistent with socioeconomic developments, play an important role in climate research (Van Vuuren and Carter, 2014). Plausible future scenarios not only represent the range of uncertainty in the climate system, but also reflect impacts on society and ecosystems, as well as the effectiveness of response options such as adaptation and mitigation under a wide range of future outcomes (Moss et al., 2010). One of the parallel tracks was the generation of climate model projections based on the four RCPs as part of Coupled Model Intercomparison Project (2010–2014) (CMIP5) (Taylor et al., 2012).

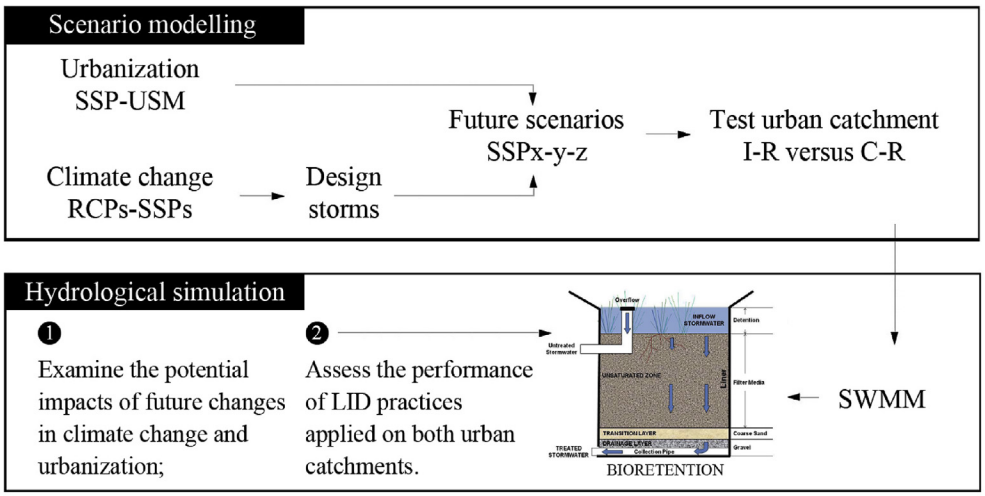

Fig. 1. Framework of study of the future scenario for urban stormwater management.

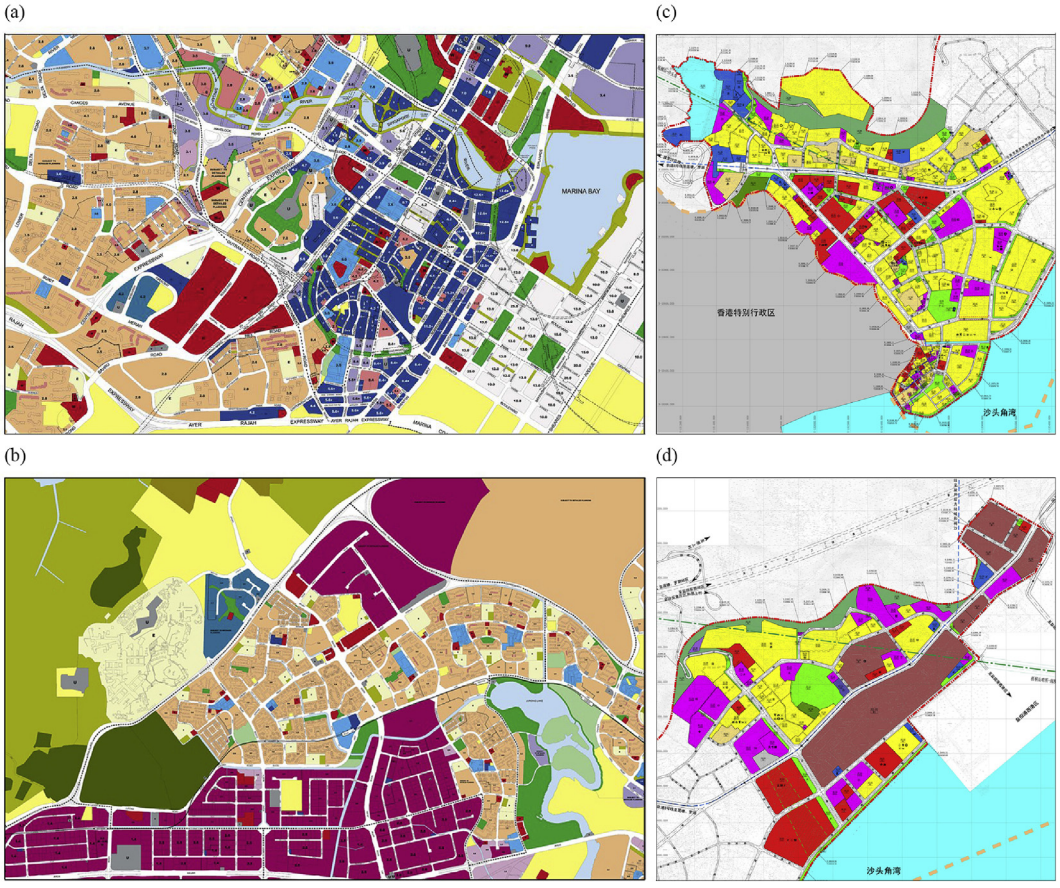

Fig. 2. Selected urban catchments: (a) Outram Park, Singapore; (b) Jurong West, Singapore; (c) Sha Tau Kok West, Shenzhen; (d) Sha Tau Kok East, Shenzhen. Notes: (a) and (b) are extracted from Urban Redevelopment Authority, Singapore (www.ura.gov.sg [accessed 15 April 2016]). (c) and (d) are extracted from Urban Planning, Land & Resources Commission of Shenzhen Municipality, Shenzhen, China (http://www.szpl.gov.cn [accessed 13 August, 2017]).

The other tracks included five shared socio-economic pathways (SSPs) describing the main characteristics of the pathway in both qualitative (O'Neill et al., 2017) and quantitative terms for key elements such as population (Samir and Lutz, 2014), economic growth (Dellink et al., 2017), urbanization (Jiang and O'Neill, 2017), emissions and land-use scenarios. Then the climate simulations and SSP-based societal futures were integrated and analysed.

In this study, we refer to climate change scenarios as SSPx–y, where x is the specific SSP and y represents the RCP. A total of 13 rational scenarios was selected (Riahi et al., 2017). Projection for the period from 2040 to 2059 was adopted. Table 3 contains a summary of the changes in rainfall intensity in these scenarios according to

Table 1
Features and characteristics of selected urban catchments.

Land-uses	Outran Park, Singapore	Jurong West, Singapore	Sha Tau Kok West, Shenzhen	Sha Tau Kok East, Shenzhen
Residential areas (ha)	19 (13.8%)	343 (23.3%)	103 (45.2%)	39 (21.4%)
Commercial areas (ha)	52 (37.7%)	5 (0.3%)	38 (16.7%)	21 (11.5%)
Industrial areas (ha)	0	439 (29.8%)	0	70 (38.4%)
Streets (ha)	22 (15.9%)	185 (12.6%)	42 (18.4%)	28 (15.4%)
Open space (ha)	41 (29.7%)	472 (32.1%)	35 (15.4%)	22 (12.1%)
Other areas (ha)	4 (2.9%)	28 (1.9%)	10 (4.3%)	2 (1.1%)
Total area (ha)	138	1472	228	182

Notes: based on web-page information published by Urban Redevelopment Authority, Singapore (www.ura.gov.sg [accessed 15 April 2016]) and Urban Planning Land & Resources Commission of Shenzhen Municipality, China (www.szpl.gov.cn [accessed 13 August, 2017]).

the equidistance quantile matching method for updating intensity-duration-frequency curves under climate change (Srivastav et al., 2014).

2.3.2. Urban development scenarios

To assess the potential local impacts of urbanization and to improve understanding of the interactions of climate change and land-use changes in USM, some studies have developed urbanization scenarios (denoted SSP-USM) including the drivers of economic activities, population, land use, technology, and policies directly associated with urban stormwater (Borris et al., 2016; Wang et al., 2016b). In this study, three SSP-USM scenarios, denoted as SSPa, SSPb, and SSPc, were adopted to reflect high, medium, and low sustainability scenarios. For these three SSP-USM scenarios, storylines of the main features of urbanization were developed following reported studies (O'Neill et al., 2014; Borris et al., 2016). According to the selected storylines (Table 4), detailed parameters of SSPs were chosen and incorporated with the master plan of Singapore and Shenzhen to mimic urban sustainable development levels, including: (1) pollutant loads due to increased density of urban population (applicable to the C-R-Singapore and C-R-Shenzhen catchments); (2) size of residential areas, open space and other areas (applicable to I-R-Singapore and I-R-Shenzhen catchments); (3) pollutant loads generated from street surface runoff caused by increased urban development; and (4) application of LID practices as sustainable stormwater management measures. The authors recognized that the scope of future urban development is highly uncertain, both for redevelopment in C-R and for new development in I-R, and considered 12 random model setups with various degrees of change in pollutant loads, land use, and LID measures.

2.3.3. Future scenarios framework

Fig. 3 elucidates how SSP-USM may be combined with SSPx-y to simulate scenarios reflecting the impacts of climate change and urbanization on stormwater management. We refer to these scenarios as SSPx-y-z, where x is the specific SSP, y represents the RCP, and z is the specific SSP-USM (SSPa, b, or c).

A total of 4212 model runs (9 databases $\times$ 39 SSPx-y-z $\times$ 12 random values) were conducted for each test catchment. For each simulation, the peak runoff and total suspended solids (TSS) load were extracted and compared with those for the baseline scenario.

Table 2
Global Climate models (GCMs) and Regional Climate Models (RCMs) selected for Singapore and Shenzhen.

GCMs	RCMs
ACCESS1-3	DDS-ACCESS1-3
Bcc_csm1-1-m	DDS-Bcc_csm1-1-m
CanESM2	DDS-CanESM2
GFDL-CM3	DDS-GFDL-CM3
GFDL-ESM2G	DDS-GFDL-ESM2G
CMCC-CM	DDS-CMCC-CM
CNRM-CM5	DDS-CNRM-CM5
CSIRO-Mk3-6-0	DDS-CSIRO-Mk3-6-0
HadGEM2-ES	DDS-HadGEM2-ES
IPSL-CM5A-MR	DDS-IPSL-CM5A-MR

Notes: source of information: Marzin et al. (2015).

2.4. Hydrology model

The Storm Water Management Model (SWMM) version 5.1 software developed by US EPA was used to obtain peak runoff and TSS loads with various bioretention scales in this study (Rossman, 2010). Within SWMM, the Green-Ampt method for infiltration, and dynamic wave routing for solving one-dimensional Saint Venant flow equations for flow routing were used (Chui et al., 2016). Manning's equation was used to calculate the runoff velocity.

Bioretention (Fig. 1) are shallow depressions in the urban landscape designed to collect and treat surface runoff. Runoff conveyed to a bioretenion is treated by filtering runoff through a densely vegetated, biologically active sand and loam filter media. In this study, bioretention was selected as a representative LID measure implemented in the test catchments. The parameters for the baseline scenario in this study are shown in Table 5. In this study, the authors selected a set of logical parameters based on earlier experience and local knowledge to produce reasonable simulated output for the baseline condition. However, rigorous calibration or verification had not been carried out due to lack of valid data on historical changes in the catchments.

3. Results and discussion

3.1. Peak runoff and TSS loads

The average peak runoff and pollution generation to the baseline scenario are summarized in Table 6 and Table 7 for a series of future scenarios simulated for test catchments following the design storms. The findings for different scenarios in test catchments depicted similar trends across various scenarios. In nearly all cases simulated, the scenarios which showed dramatic changes in climate and urbanization had higher peak runoffs and higher TSS loads. With reference to the baseline scenario, the medians of peak runoff and TSS loads are observed to have increased significantly in SSPx-y-c, and especially in SSP3-8.5-c; and decreased significantly in SSPx-y-a, and especially in SSP1-2.6-a.

For SSPx-y-c, peak runoff and TSS loading were found to become significantly larger than those in the baseline scenario (e.g., in SSP3-8.5-c, in C-R-Singapore, peak runoff was observed to have increased by 135%, 125%, and 121% and TSS loading by 176%, 163%, and 145%, corresponding to 2-, 10-, and 100-year design storms, respectively), as a result of relatively dramatic scenarios of changes in urbanization and climate. However, peak runoff and TSS loads in SSPx-y-a

Table 3
Projected changes of rainfall intensities for SSPx-y in Singapore and Shenzhen.

Singapore/Shenzhen	Minimum			Average			Maximum		
	2-yr	10-yr	100-yr	2-yr	10-yr	100-yr	2-yr	10-yr	100-yr
SSP 1–2.6 (N = 9)	2.3%/2.9%	1.8%/2.2%	0.3%/0.6%	6.3%/7.6%	5.3%/6.2%	1.9%/2.3%	12.9%/14.0%	10.5%/11.6%	4.1%/4.6%
SSP 1–4.5 (N = 9)	4.6%/4.9%	3.2%/3.8%	0.7%/1.1%	10.6%/12.0%	9.4%/10.3%	2.4%/2.9%	16.1%/18.3%	13.1%/14.3%	5.2%/5.7%
SSP 2–2.6 (N = 9)	5.6%/6.3%	4.3%/4.7%	0.9%/1.3%	10.6%/11.9%	8.7%/9.9%	2.2%/2.8%	20.8%/23.1%	17.7%/19.0%	5.0%/5.6%
SSP 2–4.5 (N = 9)	6.5%/7.1%	5.5%/5.9%	1.2%/1.6%	11.9%/13.4%	10.5%/11.2%	2.9%/3.6%	22.8%/25.2%	18.9%/19.1%	6.2%/6.9%
SSP 2–6.0 (N = 9)	6.9%/7.7%	5.7%/6.1%	1.3%/1.6%	12.4%/13.8%	10.7%/11.9%	3.0%/3.8%	22.8%/25.1%	18.9%/19.3%	6.4%/7.0%
SSP 3–4.5 (N = 9)	8.0%/8.4%	6.1%/6.3%	1.4%/1.9%	12.3%/13.6%	10.5%/11.3%	3.0%/3.7%	22.5%/24.8%	20.8%/22.0%	6.5%/7.2%
SSP 3–6.0 (N = 9)	8.4%/8.7%	6.5%/6.8%	1.6%/1.7%	13.2%/14.8%	11.0%/11.9%	3.3%/3.9%	24.5%/25.1%	21.8%/23.4%	6.9%/7.6%
SSP 3–8.5 (N = 9)	9.7%/9.9%	6.7%/7.2%	1.8%/2.1%	15.6%/17.0%	12.6%/13.7%	3.9%/4.6%	29.9%/32.3%	26.1%/27.8%	8.2%/9.0%
SSP 4–2.6 (N = 9)	5.6%/6.1%	4.3%/4.9%	1.5%/1.9%	10.6%/12.0%	8.7%/9.6%	2.4%/3.1%	20.8%/23.1%	17.7%/19.6%	5.1%/5.6%
SSP 4–4.5 (N = 9)	6.5%/7.1%	5.5%/6.2%	1.6%/2.1%	9.9%/11.0%	9.5%/10.4%	2.7%/3.4%	20.3%/22.9%	16.2%/17.8%	5.9%/6.7%
SSP 4–6.0 (N = 9)	7.9%/8.3%	6.6%/6.9%	1.7%/2.2%	10.4%/11.8%	9.7%/10.5%	2.9%/3.5%	21.2%/23.8%	16.8%/18.1%	6.2%/6.8%
SSP 5–4.5 (N = 9)	7.7%/8.2%	5.8%/6.2%	1.6%/2.0%	11.6%/13.0%	9.8%/10.7%	3.0%/3.8%	20.5%/23.0%	19.8%/21.0%	6.5%/7.3%
SSP 5–6.0 (N = 9)	8.2%/8.6%	6.1%/6.4%	1.7%/2.1%	12.1%/13.6%	10.2%/11.1%	3.2%/3.9%	22.5%/25.4%	20.9%/22.1%	7.1%/8.2%

Notes: source of information published by Meteorological Service, Singapore, and Meteorological Bureau of Shenzhen Municipality, China (www.weather.gov.sg [accessed 25 Jan. 2017], and www.szmb.gov.cn [accessed 15 August, 2017]) and Srivastav et al. (2014).

were found to be clearly smaller than those in the baseline scenario as a result of relatively small changes in urbanization, and utilization of various well-designed LID practices incorporated in this scenario. A case in point is the scenario of SSP1-2.6-a in the I-R-Singapore catchment, in which the average rate of decrease in runoff of 34%, 29%, and 24% corresponding to the 2-, 10-, and 100-year design storms, respectively, for small changes in climate (SSP1-2.6 represents a low-emissions scenario with a slow pace of climatic changes) and urbanization (slight increases in imperviousness and TSS loads, as well as LID measures applied sustainably) were observed.

The average changes in peak volume in future scenarios are smaller than those in TSS loads for design storms (Tables 6 and 7). For example, in SSP3-8.5-c, the increase in peak volume (135.25%) is smaller than that of TSS loads (176.48%) corresponding to the 2-year design storm in the C-R-Singapore catchment. This observation shows that uncertain future changes will lead to more serious effects on the quality of urban runoff than on quantity, due not only to the increase in runoff carrying non-point source pollution but also the increased pollutant loads generated from urban land-uses transformation and intensification.

As are to be expected, the results of the SSPx-y-b analysis reflect an intermediate pathway between SSPx-y-a and SSPx-y-c, see Figs. 4 and 5. The peak runoff increased slightly in test catchments as rainfall intensity increased and land use changed in SSPx-y-b (i.e., converting open space and other areas into residential areas in I-R). However, there were different findings in terms of deterioration of water quality in C-R as pollutant load density increased following land-use changes in C-R (more residential area and impervious surface). The commercial and residential (C-R) land use in downtown areas put more pressure on the management of stormwater than that of the industrial and residential (I-R) land use in developing areas. This is to be expected as urbanization tends to lead to higher pollution loads. I-R could provide more flexibility in the urbanization strategy because of more readily available spaces for development.

It was noted that, due to different development processes, the influence of peak runoff and TSS loads was found to be more significant in Shenzhen than in Singapore, be it in C-R catchments or in I-R catchments, based on the comparison in Figs. 4 and 5. For example, the average fluctuate of TSS loads from SSP3-8.5-c to SSP1-2.6-a following the 2-year storm events, the range of

Table 4
Characteristics of SSPa, SSPb, and SSPc, as well as detail parameters of SSPs for C-R and/or I-R.

	SSP a	SSP b	SSP c
Sustainability [a]	High	Median	Low
Population growth [a]	Low	Median	High
Economic [a]	High	Median	Low
Technology [a]	High	Median	Low
Education [a]	High	Median	Low
Changes of pollutant loads from residential and commercial land-uses (C-R) [b]	−10.0%–20.0% for C-R-Singapore, −15.0%–15.0% for C-R-Shenzhen	−2.5%–27.5% for C-R-Singapore, −7.5%–32.5% for C-R-Shenzhen	5.0%–35.0% for C-R-Singapore, 7.5%–42.5% for C-R-Shenzhen
Changes of size for land-uses (I-R) [b]	Industrial areas may be decreased by 5.0%–35.0%, and 10.0%–40.0% for I-R-Singapore and I-R-Shenzhen respectively, and other areas may be inclined correspondingly	Industrial areas may be decreased by −2.5% to 27.5%, and −10.0% to 20.0% for I-R-Singapore and I-R-Shenzhen respectively, and other areas may be inclined correspondingly	Industrial areas may be decreased by −10.0% to 20.0%, and −25.0% to 5.0% for I-R-Singapore and I-R-Shenzhen respectively, and other areas may be declined correspondingly
Changes of pollutant loads from street [b]	No change	10.0%–40.0%	35.0%–65.0%
The area of LID practices applied for total residential, commercial, industrial land-uses and street [b]	5.0%–10.0%	0 to 5.0%	No more

Notes:
[a] Source of sustainability, population growth, economic, technology and education are from O'Neill et al. (2014) and Kriegler et al. (2012).
[b] Source of information are from Borris et al. (2016) and Wang et al. (2016b).

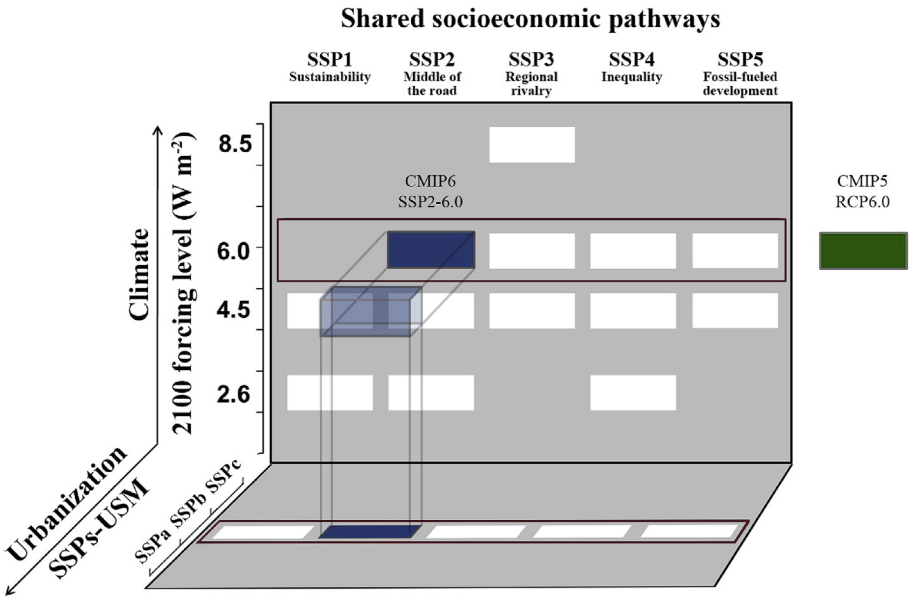

Fig. 3. Future scenarios framework. Note: The figure provides a visualization on how SSPx-y-z can be combined with climate simulations from CMIP6, using the case of a forcing pathway stabilizing at 6.0 W m^{-2}. The full set of multiple SSPs, RCPs and SSP-USM can be used to form a matrix of plausible integrated scenarios (van Vuuren et al., 2012, 2014; Kriegler et al., 2012).

fluctuation in C-R-Shenzhen is 132% while it is 106% in C-R-Singapore. One may conclude that rapidly growing population and urbanization could lead to greater uncertainty and instability for stormwater management in the near future, especially for the urban catchments in the developing countries.

3.2. Relative impacts of climate change and urbanization

In this study, climate change and urbanization were incorporated as two major factors influencing in flow quantity and water quality in the selected future scenarios. Cumulative uncertainties in peak runoff and TSS loads for SSPx-y (climate change) and SSPz (urbanization) were examined separately and the findings are shown for C-R and I-R in Figs. 6 and 7. One may note from Figs. 6 and 7 that changes in the impacts of SSPz produced significantly higher variability in peak runoff and water quality than that attributable to changes in SSPx-y, and it is especially so for water quality.

Hence, one may conclude that the flow quantity and water quality are more sensitive to changes in land use, the degree of

Table 5
Parameters corresponding to surface imperviousness, water quality and LID for different land-uses adopted in SWMM.

Parameter		Residential areas	Commercial areas	Industrial areas	Street	Open space & other areas
Features of land-uses	Impervious rate (%)	70.00	70.00	70.00	95.00	30.00
	Depth of depression storage on pervious area (mm)	5.00	5.00	5.00	0.05	30.00
Quality [a]	TSS (mg/L)	50	50	50	50	50
MPB [b]	TSS (kg/ha)	13.50	29.78	24.61	30.38	16.27
Rate constant [b]	TSS	0.40	0.40	0.40	0.40	0.40
WCt [b]	TSS	0.0023	0.5063	0.94	0.51	0.006
RE in washoff function [b]	TSS	1.8423	0.50	0.3753	0.50	1.20
Surface of LID [c]	Berm height (mm)	150.00	150.00	150.00	150.00	–
	Vegetation volume fraction	0.10	0.10	0.10	0.10	–
	Surface roughness	0.10	0.10	0.10	0.10	–
	Surface slope (%)	1.00	1.00	1.00	1.00	–
Soil of LID [c]	Thickness of soil (mm)	1200	1200	1200	1200	–
	Porosity	0.50	0.50	0.50	0.50	–
	Field capacity	0.20	0.20	0.20	0.20	–
	Wilting point	0.10	0.10	0.10	0.10	–
	Conductivity (mm/h)	250	250	250	250	–
	Conductivity slope	10.0	10.0	10.0	10.0	–
	Suction head (mm)	87.5	87.5	87.5	87.5	–
Storage of LID[c]	Thickness of storage (mm)	500	500	500	500	–
	Void ratio (voids/solids)	0.75	0.75	0.75	0.75	–
	Seepage rate (mm/h)	750	750	750	750	–
	Clogging factor	0	0	0	0	–
Drain of LID[c]	Flow coefficient of drain	0.50	0.50	0.50	0.50	–
	Flow exponent of drain	0.50	0.50	0.50	0.50	–
	Offset height of drain (mm)	150	150	150	150	–

Notes: MPB (Maximum possible buildup), WC (Washoff coefficient), RE(Runoff exponent).
[a] Parameters of quality are from Public Utilities Board, Singapore (www.pub.gov.sg [accessed 27 March 2016]).
[b] Parameters of maximum possible buildup, rate constant, washoff coefficient, and runoff exponent in washoff function of TSS, COD, TN and TP are from Zhang and Yamada (1996).
[c] Parameters of surface, soil, storage, and drain are from Chui et al. (2016).

Table 6
Changes in average peak runoff and TSS loads generation for the various scenario in C-R-Singapore and I-R-Singapore as compared to those of baseline scenario.

Catchment	Scenario	2-yr design storm		10-yr design storm		100-yr design storm		Catchment	Scenario	2-yr design storm		10-yr design storm		100-yr design storm	
		Peak runoff (%)	TSS (%)	Peak runoff (%)	TSS (%)	Peak runoff (%)	TSS (%)			Peak runoff (%)	TSS (%)	Peak runoff (%)	TSS (%)	Peak runoff (%)	TSS (%)
C-R-Singapore	SSP1-2.6-a	73.63	70.14	96.02	81.33	98.91	88.44	I-R-Singapore	SSP1-2.6-a	66.00	66.55	70.56	72.50	75.96	73.20
	SSP1-4.5-a	77.57	73.05	98.29	82.58	99.06	90.41		SSP1-4.5-a	67.66	68.62	71.29	73.08	76.19	74.28
	SSP2-2.6-a	78.46	74.02	98.24	83.95	99.87	90.49		SSP2-2.6-a	67.50	69.84	71.76	74.04	77.86	75.14
	SSP2-4.5-a	79.36	74.35	99.01	84.17	100.21	92.01		SSP2-4.5-a	70.91	70.30	73.14	75.96	78.34	76.26
	SSP2-6.0-a	79.41	75.49	99.34	84.32	100.76	92.38		SSP2-6.0-a	69.77	70.94	73.22	75.48	78.77	77.28
	SSP3-4.5-a	80.39	76.89	99.67	85.22	101.31	92.81		SSP3-4.5-a	69.77	71.68	74.43	76.57	79.83	77.52
	SSP3-6.0-a	81.15	77.08	100.09	85.30	101.35	95.02		SSP3-6.0-a	70.76	73.08	74.71	76.64	80.31	81.24
	SSP3-8.5-a	82.99	78.79	100.53	85.48	103.19	96.88		SSP3-8.5-a	71.79	73.38	75.35	77.93	81.52	84.37
	SSP4-2.6-a	78.04	73.12	98.09	84.10	100.98	93.05		SSP4-2.6-a	68.86	69.70	71.29	74.89	77.39	75.81
	SSP4-4.5-a	78.49	75.77	99.36	84.87	101.45	93.48		SSP4-4.5-a	69.24	70.31	73.03	75.99	78.33	76.29
	SSP4-6.0-a	79.97	76.70	100.07	85.22	101.72	95.02		SSP4-6.0-a	72.11	71.99	74.57	76.86	79.27	77.26
	SSP5-4.5-a	80.25	77.08	99.63	84.83	102.79	94.18		SSP5-4.5-a	71.02	71.72	73.67	76.40	79.97	78.40
	SSP5-6.0-a	80.53	77.43	99.58	85.17	102.98	94.67		SSP5-6.0-a	70.48	72.13	73.45	76.35	80.15	83.35
	SSP1-2.6-b	108.69	125.79	109.91	120.00	103.21	108.95		SSP1-2.6-b	100.58	96.13	103.89	94.14	102.12	92.14
	SSP1-4.5-b	110.53	127.35	111.43	121.17	104.59	109.63		SSP1-4.5-b	102.81	97.93	105.79	96.95	103.49	95.95
	SSP2-2.6-b	113.44	130.19	112.66	123.18	106.62	110.49		SSP2-2.6-b	105.52	100.45	107.73	98.08	105.33	96.28
	SSP2-4.5-b	112.77	131.60	113.56	124.62	106.89	112.96		SSP2-4.5-b	107.57	100.69	109.09	99.41	107.59	98.41
	SSP2-6.0-b	114.47	132.27	113.93	123.88	107.21	113.88		SSP2-6.0-b	108.03	100.55	109.90	99.93	107.20	99.12
	SSP3-4.5-b	115.81	134.79	114.46	125.67	110.45	115.54		SSP3-4.5-b	109.73	102.96	110.12	101.70	108.52	100.17
	SSP3-6.0-b	117.07	135.66	115.52	125.65	111.21	118.69		SSP3-6.0-b	110.65	104.13	111.30	102.18	109.04	107.28
	SSP3-8.5-b	118.58	137.36	115.41	127.53	112.99	120.13		SSP3-8.5-b	111.71	106.77	111.32	104.21	109.72	108.24
	SSP4-2.6-b	112.32	130.27	112.55	122.13	104.31	109.56		SSP4-2.6-b	105.54	100.53	107.69	98.42	109.79	96.12
	SSP4-4.5-b	113.94	131.59	114.04	123.65	105.78	110.21		SSP4-4.5-b	106.50	100.79	109.04	99.65	109.56	97.25
	SSP4-6.0-b	114.86	132.57	115.36	125.83	107.12	112.98		SSP4-6.0-b	107.18	102.62	110.91	101.49	109.71	100.49
	SSP5-4.5-b	115.39	133.00	114.79	124.90	107.01	114.41		SSP5-4.5-b	108.81	103.52	110.50	100.60	109.59	105.76
	SSP5-6.0-b	116.42	134.94	114.40	125.78	108.89	117.55		SSP5-6.0-b	109.67	103.45	111.24	102.15	110.74	107.95
	SSP1-2.6-c	123.32	161.67	116.95	151.67	112.05	135.02		SSP1-2.6-c	118.56	157.15	116.69	132.05	105.68	122.15
	SSP1-4.5-c	127.43	165.47	121.67	157.78	113.15	142.29		SSP1-4.5-c	124.41	161.61	121.31	136.85	108.78	125.19
	SSP2-2.6-c	127.96	166.26	120.64	156.43	113.28	140.99		SSP2-2.6-c	123.73	162.09	120.62	135.58	109.97	127.82
	SSP2-4.5-c	129.13	168.00	123.10	159.98	114.20	144.25		SSP2-4.5-c	126.86	163.37	123.30	138.70	110.67	131.31
	SSP2-6.0-c	129.25	169.89	123.10	159.72	115.62	147.92		SSP2-6.0-c	127.57	166.42	124.10	138.92	111.64	132.29
	SSP3-4.5-c	129.61	170.51	122.70	159.13	116.17	149.53		SSP3-4.5-c	128.55	166.93	124.36	140.70	111.99	133.47
	SSP3-6.0-c	130.14	172.18	123.16	160.20	118.75	152.86		SSP3-6.0-c	129.99	168.23	125.31	140.57	112.74	135.25
	SSP3-8.5-c	135.25	176.48	125.34	162.95	120.92	157.12		SSP3-8.5-c	133.40	171.60	126.88	142.02	114.21	138.22
	SSP4-2.6-c	127.88	166.46	121.30	157.30	113.11	143.58		SSP4-2.6-c	123.82	163.24	121.07	136.77	109.45	126.13
	SSP4-4.5-c	126.54	166.86	121.91	158.55	114.37	146.21		SSP4-4.5-c	124.19	160.85	122.75	137.97	110.02	128.47
	SSP4-6.0-c	126.40	167.55	122.84	157.88	115.29	145.21		SSP4-6.0-c	125.62	162.46	123.00	138.59	112.99	131.94
	SSP5-4.5-c	128.16	169.78	122.18	159.67	117.20	150.69		SSP5-4.5-c	126.72	167.61	123.34	138.40	118.77	133.29
	SSP5-6.0-c	128.55	171.62	122.86	159.97	118.46	153.01		SSP5-6.0-c	128.57	169.38	124.75	138.86	119.10	136.62

Table 7
Comparisons changes of average peak runoff and TSS loads generation for the various scenario in C-R-Shenzhen and I-R-Shenzhen as compared to those of baseline scenario.

Catchment	Scenario	2-yr design storm		10-yr design storm		100-yr design storm		Catchment	Scenario	2-yr design storm		10-yr design storm		100-yr design storm	
		Peak runoff (%)	TSS (%)	Peak runoff (%)	TSS (%)	Peak runoff (%)	TSS (%)			Peak runoff (%)	TSS (%)	Peak runoff (%)	TSS (%)	Peak runoff (%)	TSS (%)
C-R-Shenzhen	SSP1-2.6-a	73.52	64.15	88.17	71.46	93.21	82.54	I-R-Shenzhen	SSP1-2.6-a	59.30	56.75	66.26	65.10	71.36	70.23
	SSP1-4.5-a	73.87	67.87	90.12	72.68	94.36	83.51		SSP1-4.5-a	61.26	60.23	67.39	67.83	72.12	71.23
	SSP2-2.6-a	74.16	66.81	90.36	73.49	94.87	84.92		SSP2-2.6-a	62.53	61.74	67.76	68.24	73.23	72.44
	SSP2-4.5-a	74.01	67.51	91.07	74.74	95.38	86.41		SSP2-4.5-a	65.12	63.33	71.14	70.96	74.34	74.46
	SSP2-6.0-a	73.51	68.1	91.12	74.89	94.36	87.78		SSP2-6.0-a	65.47	64.21	72.12	71.82	75.77	75.26
	SSP3-4.5-a	73.59	68.31	92.61	75.12	95.33	87.21		SSP3-4.5-a	66.42	65.82	73.42	72.37	75.83	76.42
	SSP3-6.0-a	75.10	68.52	92.89	75.72	96.42	88.32		SSP3-6.0-a	67.26	65.98	74.13	74.44	78.31	77.23
	SSP3-8.5-a	73.21	68.59	93.51	76.17	96.19	87.88		SSP3-8.5-a	67.39	64.28	74.55	75.33	79.52	78.46
	SSP4-2.6-a	73.39	67.91	90.72	75.81	97.38	86.05		SSP4-2.6-a	68.46	65.32	69.29	68.29	75.39	74.41
	SSP4-4.5-a	74.17	68.11	91.16	75.9	98.25	87.42		SSP4-4.5-a	69.13	67.31	70.23	69.34	75.33	75.2
	SSP4-6.0-a	76.15	68.71	92.37	76.12	99.12	88.02		SSP4-6.0-a	70.41	68.59	72.57	70.1	75.27	75.66
	SSP5-4.5-a	76.75	69.23	91.36	75.85	98.79	89.18		SSP5-4.5-a	70.45	68.72	72.37	72.43	78.97	77.42
	SSP5-6.0-a	73.52	70.17	90.89	76.17	97.98	89.97		SSP5-6.0-a	70.87	69.59	72.56	73.32	80.15	79.32
	SSP1-2.6-b	113.61	138.10	105.91	127.97	100.22	114.35		SSP1-2.6-b	108.29	118.23	103.49	104.24	102.19	96.44
	SSP1-4.5-b	114.83	139.17	106.54	130.51	100.59	115.32		SSP1-4.5-b	109.29	119.92	105.92	105.45	104.52	99.45
	SSP2-2.6-b	117.26	141.18	110.48	132.73	102.32	117.91		SSP2-2.6-b	111.33	121.25	109.32	106.46	106.22	100.18
	SSP2-4.5-b	118.56	142.62	113.17	133.08	102.89	118.62		SSP2-4.5-b	112.59	122.63	111.27	109.42	108.71	102.16
	SSP2-6.0-b	118.93	143.88	114.25	134.71	103.21	122.28		SSP2-6.0-b	113.43	123.45	112.53	109.43	109.35	103.42
	SSP3-4.5-b	119.60	145.07	115.18	136.91	105.45	124.43		SSP3-4.5-b	115.24	125.98	113.43	113.79	110.49	104.72
	SSP3-6.0-b	121.22	144.45	117.17	137.61	107.23	126.91		SSP3-6.0-b	116.39	129.43	114.56	116.98	110.16	106.83
	SSP3-8.5-b	121.48	143.23	119.46	140.62	110.39	130.33		SSP3-8.5-b	117.22	135.37	115.72	119.61	111.32	107.45
	SSP4-2.6-b	118.25	139.43	112.82	132.71	101.61	117.62		SSP4-2.6-b	108.29	122.56	106.24	108.32	106.24	101.29
	SSP4-4.5-b	119.34	141.25	113.01	133.94	102.28	118.19		SSP4-4.5-b	112.27	125.29	118.10	110.54	105.50	100.53
	SSP4-6.0-b	121.63	142.43	115.87	134.72	104.21	122.80		SSP4-6.0-b	113.25	128.35	111.19	116.29	108.49	104.25
	SSP5-4.5-b	119.39	143.20	116.17	135.13	105.41	124.16		SSP5-4.5-b	114.14	130.22	112.31	117.35	109.91	103.25
	SSP5-6.0-b	120.14	145.98	117.01	136.42	108.91	126.53		SSP5-6.0-b	115.34	132.59	114.37	118.35	110.73	104.51
	SSP1-2.6-c	131.27	183.71	121.89	166.81	117.29	142.15		SSP1-2.6-c	128.36	168.35	123.95	152.05	111.28	125.28
	SSP1-4.5-c	135.75	188.74	126.21	172.82	122.11	145.19		SSP1-4.5-c	133.23	172.41	128.71	161.85	114.12	133.21
	SSP2-2.6-c	136.67	189.61	128.24	171.49	123.46	147.82		SSP2-2.6-c	133.93	174.29	122.43	162.58	118.97	130.91
	SSP2-4.5-c	137.83	191.17	130.4	172.25	125.2	149.31		SSP2-4.5-c	134.26	176.32	123.08	163.70	122.87	132.35
	SSP2-6.0-c	138.17	192.11	132.18	172.19	128.08	151.29		SSP2-6.0-c	137.12	180.24	124.71	164.92	121.64	134.92
	SSP3-4.5-c	138.92	192.50	135.32	173.97	130.12	158.47		SSP3-4.5-c	137.56	179.43	124.09	165.30	122.29	136.33
	SSP3-6.0-c	139.41	193.11	136.11	175.62	131.91	160.25		SSP3-6.0-c	138.42	181.53	125.81	167.37	123.34	138.56
	SSP3-8.5-c	144.52	195.71	139.28	178.27	134.58	165.22		SSP3-8.5-c	140.42	182.42	126.42	170.02	124.61	147.82
	SSP4-2.6-c	136.17	183.72	120.47	169.74	126.17	149.13		SSP4-2.6-c	132.72	170.54	123.29	160.47	121.35	133.18
	SSP4-4.5-c	137.45	185.63	120.25	170.41	127.32	152.47		SSP4-4.5-c	133.89	172.31	124.92	162.67	122.92	136.71
	SSP4-6.0-c	138.12	188.65	128.5	172.84	127.09	153.94		SSP4-6.0-c	135.22	175.26	124.72	167.49	121.49	139.26
	SSP5-4.5-c	140.78	190.71	129.42	174.82	129.27	161.29		SSP5-4.5-c	136.28	179.31	124.37	168.50	123.47	142.29
	SSP5-6.0-c	142.91	192.20	134.25	175.13	131.51	164.62		SSP5-6.0-c	137.71	180.38	124.98	169.86	124.11	144.49

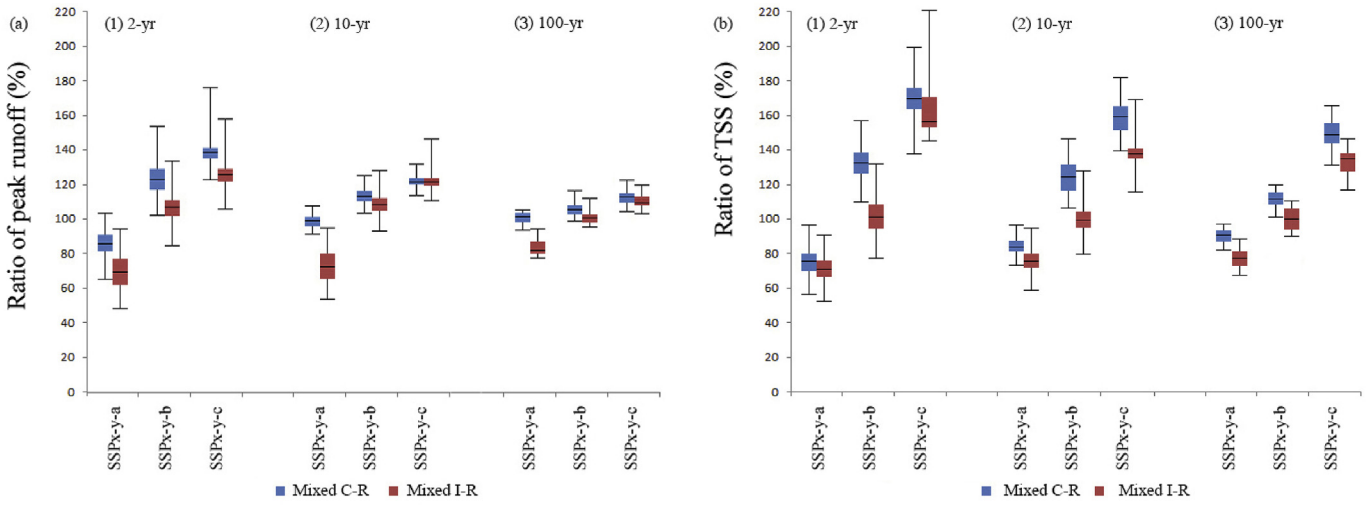

Fig. 4. Ratios (%) of peak runoff and TSS loads from C-R-Singapore and I-R-Singapore based on future scenarios (SSPx-y-a, SSPx-y-b, SSPx-y-c). Note: In these boxplots, the base of box denotes the first quartile (Q1, 25%), the line in the central part of the box indicates the median (50%), and the roof marks the 3rd quartile (Q3, 75%). Large variability of flow quantity and water quality is found, as indicated by the upper and lower ends of the whiskers.

urbanization (intensity of land use) and LID measures adopted than to climate change. Other published work focusing on stormwater quantity and quality reported similar findings (Lafontaine et al., 2015; Borris et al., 2016; Wang et al., 2016b). One may also conclude that the pace and degree of urbanization is an important and crucial factor in evaluating socio-economic impact in the development of an urban catchment, and it underlines the importance of the pace and change of land use in developing a rational plan for sustainable urbanization.

Some researches indicated that climate change may lead to larger impact and particularly for rainfall corresponding to longer return periods, at least in mid-latitudes (Pagliara et al., 1998; Crisci et al., 2002; Kim and Choi, 2011). However, this phenomenon is not observed in the present study. Upon comparing the three design storms with respect to their response to future scenarios, the variability (Q3-Q1) of peak volume and TSS loads were found to be higher for the 2-, and 10-year design storm than those for the 100-year design storm (see Figs. 6 and 7). Thus the adverse influences of urbanization and climatic changes may be more severe for design storms corresponding to shorter return period. This may be the results of relatively higher variability for shorter-return storm events caused by climate change in the test catchments. It was also noted that the variability here refers to changes in percentage rather than changes in absolute value. Urban catchments may be put under higher stress and challenges by these more frequent storms, if storms of shorter return periods are affected more significantly than storms of longer return periods. Wang et al. (2016b) who investigated the cost-effectiveness of bioretention for future scenarios, also reported similar findings.

3.3. *Performance of LID practices in future scenarios*

LID practices were adopted in the test catchments as a measure to counter the effects of urbanization and climate change, and to improve runoff water quality. Although the performance of LID is strongly dependent on environmental conditions, certain LID

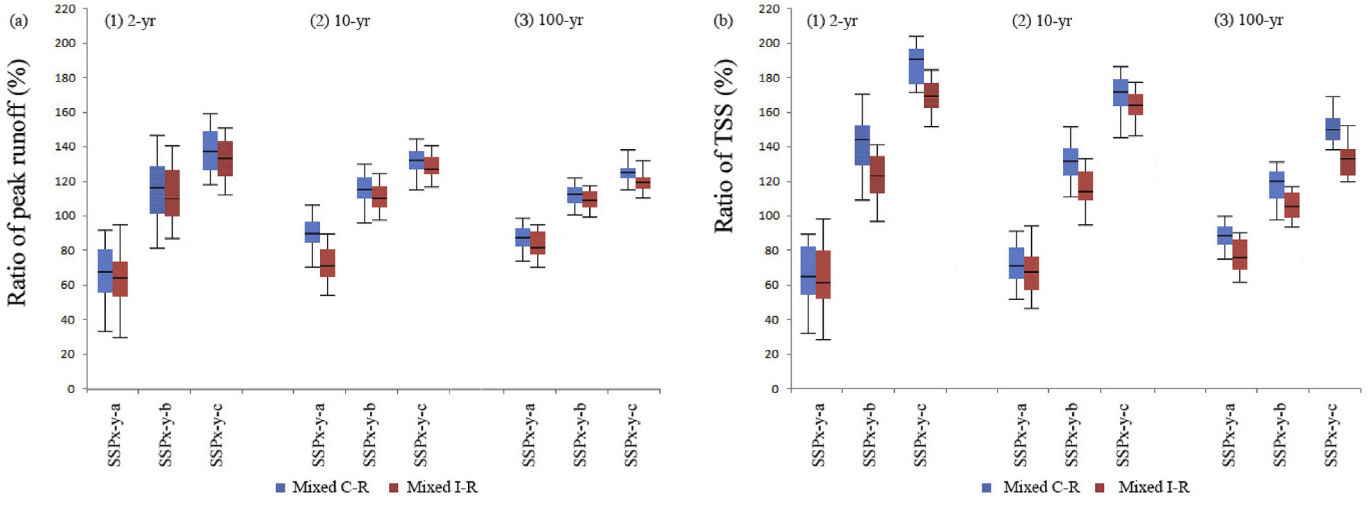

Fig. 5. Ratios of peak runoff and TSS loads from C-R-Shenzhen and I-R-Shenzhen on future scenarios (SSPx-y-a, SSPx-y-b, SSPx-y-c). Note: In these boxplots, the base of box denotes the first quartile (Q1, 25%), the line in the central part of the box indicates the median (50%), and the roof marks the 3rd quartile (Q3, 75%). Large variability of flow quantity and water quality is found, as indicated by the upper and lower ends of the whiskers.

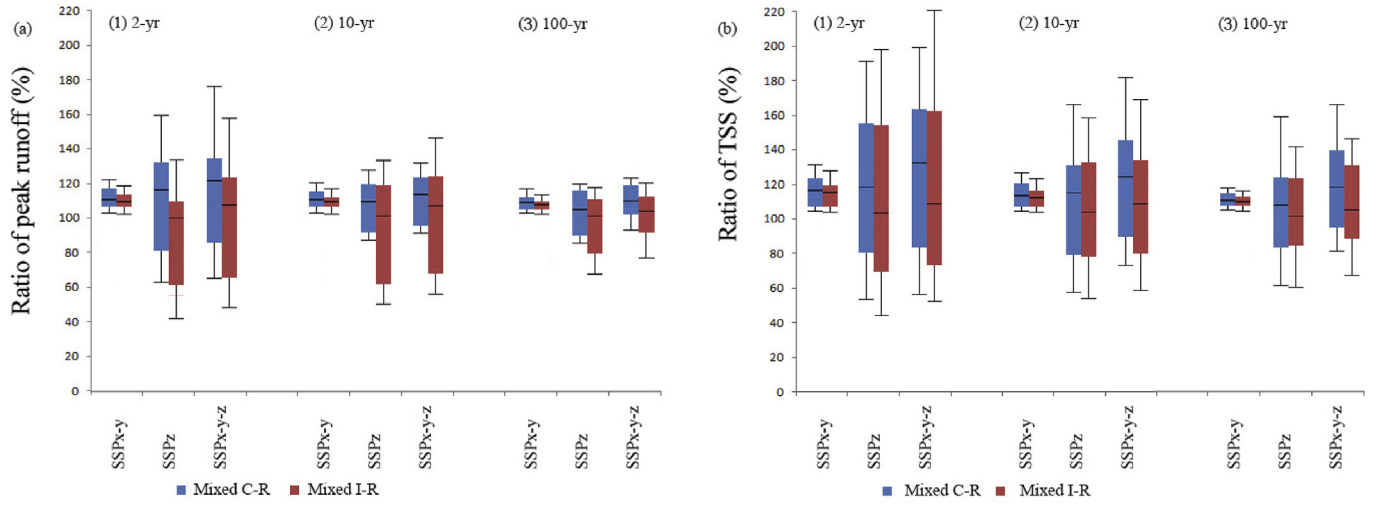

Fig. 6. Ratios of peak runoff and TSS loads from C-R-Singapore and I-R-Singapore based on future scenarios (SSPx-y, SSPz, SSPx-y-z). Note: In these boxplots, the base of box denotes the first quartile (Q1, 25%), the line in the central part of the box indicates the median (50%), and the roof marks the 3rd quartile (Q3, 75%). Large variability of flow quantity and water quality is found, as indicated by the upper and lower ends of the whiskers.

practices such as bioretention could cap or reduce peak runoff and reduce pollutant loads. Ahiablame et al. (2012) reported peak flow reduction of 32%–99% using bioretention. Guan et al. (2015) reported that LID practices appeared to be effective in controlling flow quantity and water quality of runoff and mitigating the negative impacts of rapid urbanization. To assess the performance of LID practices in future scenarios, the influences of bioretention with different scales applied to SSPx-y-z were simulated.

In this study, only simulations for assessing the performance of LID measures adopted in the catchments in Singapore were carried out as the focus of the study was to establish the difference and elucidate the various degree of performances following various scales of bioretention applied in the future scenarios. The performance curves (i.e., scales of bioretention versus changes in peak runoff and TSS loads) of 2-, 10-, and 100-year design storms for future scenarios in the C-R and I-R catchments in Singapore are shown in Fig. 8. These S-shaped curves decrease generally with exponential regression, suggesting that LID practices could alleviate the pressures on stormwater management. Although the area of the selected urban catchment was constant, different future scenarios would result in changes in peak runoff, corresponding to the increase in TSS loads. However, more bioretention reduces peak runoff and TSS concentration as depicted in the various S-curves corresponding to different scenarios.

In this study, the main objective of LID practices is targeted at maintaining peak runoff and TSS loads in 2-,10-, and 100-year storm events for future scenarios. In order to control the peak runoff in C-R catchments, the optimal bioretention areas of 7.2%, 6.7%, and 8.6% for the corresponding 2-, 10, and 100-year design storms, respectively may be adopted. . For 75% of scenarios under the baseline condition, optimal bioretention area ranges approximately from 3.2% to 6.8% in Singapore. In terms of the water quality, the optimal bioretention areas are 6.3%, 6.8%, and over 10.0% for 2-, 10-, and 100-year storm events, respectively to achieve removal of TSS loads in all scenarios. LID measures with limited retention capacity are mainly adopted to cater to shorter return period design

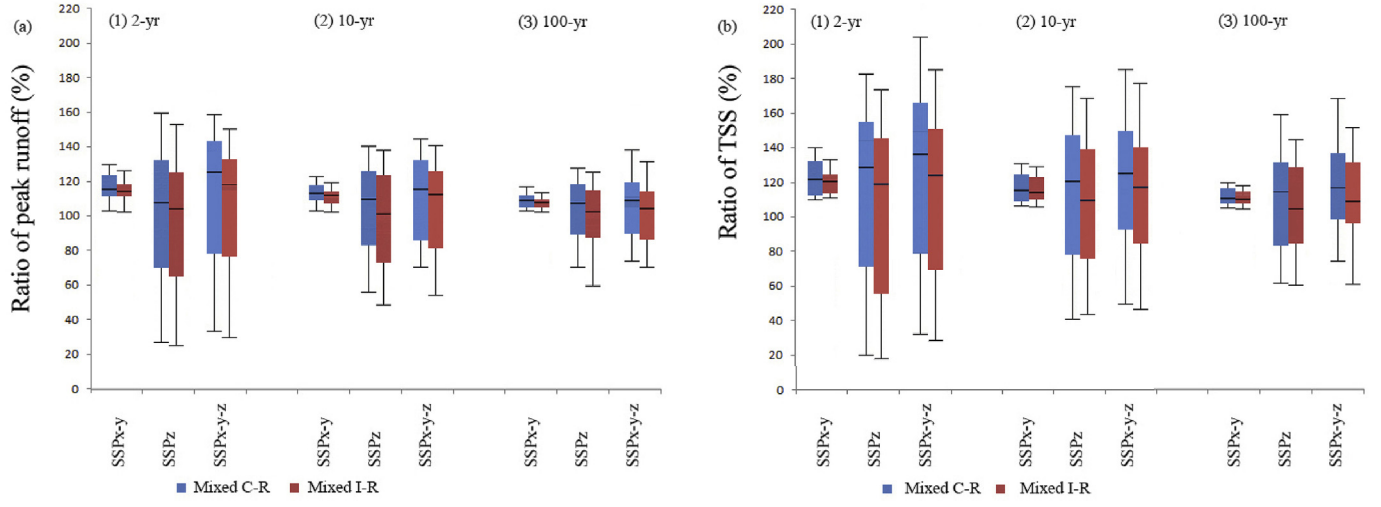

Fig. 7. Ratios of peak runoff and TSS loads from C-R-Shenzhen and I-R-Shenzhen based on future scenarios (SSPx-y, SSPz, SSPx-y-z). Note: In these boxplots, the base of box denotes the first quartile (Q1, 25%), the line in the central part of the box indicates the median (50%), and the roof marks the 3rd quartile (Q3, 75%). Large variability of flow quantity and water quality is found, as indicated by the upper and lower ends of the whiskers.

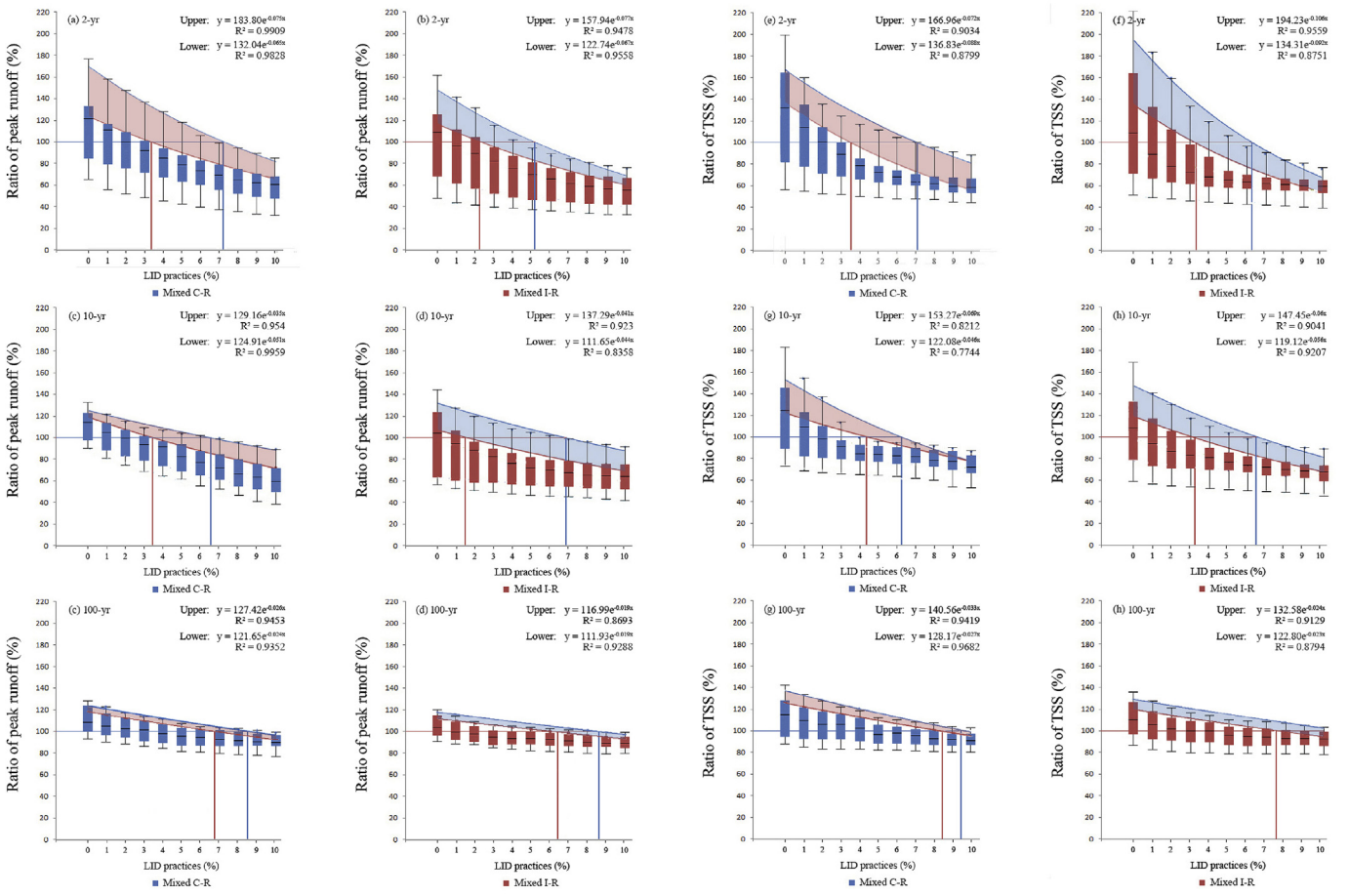

Fig. 8. Performance of LID practices for C-R-Singapore and I-R-Singapore based on 2-, 10-, and 100-year design storms under various future scenarios.

storm (for example, 2-year design storm event). Incremental bio-retention measure would obviously produce relatively small incremental improvement on hydrological performance However, the findings of this study show that the effect is not obvious when the scale exceeds 7%. Whereas an appropriate sustainability strategy will result in better control of runoff flow quantity and water quality. In summary, to alleviate the adverse effects of future changes and ensure the effectiveness of LID. The latter should be well designed in accordance to the findings of future scenario modeling.

4. Conclusions and recommendations

Future scenario modeling of urban stormwater in terms of flow quantity and water quality was carried out to evaluate the effects of climate change and urbanization in selected urban catchments. Several future scenarios were selected based on a framework of RCPs, SSPs and SSP-USM.

Based on the findings of future scenarios modeling, the authors observe that impacts of SSPx-y-c are significant and are more adverse than that for SSPx-y-a. In terms of stormwater quantity and quality, highly developed and dense commercial and residential land-use in downtown area will be more difficult to manage than that in industrial and residential areas. Storms corresponding to shorter return period are found to produce more significant impacts than storms of longer return periods. The impacts of urbanization are more severe and adverse than that of climate change. Likewise, uncertain future changes will lead to more significant effects on the quality of urban runoff than on quantity. In addition, the influence from catchments with relatively rapid developing rates appeared to be more significant. Finally, adopting the appropriate LID practices as source management measure would result in better control of runoff quantity and water quality for storms corresponding to shorter return.

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